RF MEMS AND THEIR APPLICATIONS IN NASA's SPACE COMMUNICATION SYSTEMS

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I. INTRODUCTION

RF and microwave communication systems rely on frequency, amplitude, and phase control circuits to efficiently use the available spectrum. Phase control circuits are required for electronically scanning phased array antennas that enable radiation pattern shaping, scanning, and hopping. Two types of phase shifters, which are the phase control circuits, are most often used. The first is comprised of two circuits with different phase characteristics such as two transmission lines of different lengths or a high pass and low pass filter and a switch that directs the RF power through one of the two circuits. Alternatively, a variable capacitor, or varactor, is used to change the effective electrical path length of a transmission line, which changes the phase characteristics. Filter banks are required for the diplexer at the front end of wide band communication satellites. These filters greatly increase the size and mass of the RF /microwave systems, but smaller diplexers may be made with a low loss varactor or a group of capacitors, a switch and an inductor.

Traditionally, solid-state electronic devices such as GaAs MESFETs and varactor diodes are used for these purposes. While these devices have performed well and enabled great leaps in radar and communication technologies, they do have several problems. They rely on control of current through a semiconductor junction or a metal/semiconductor junction. There is a resistive loss associated with charge flow through the junctions, and this resistive loss consumes substantial DC and RF power. For example, approximately 0.5 dB of RF power is lost through each GaAs MESFET switch. This consumed power generates heat that must be dissipated, which adds to the system size and complexity. Lastly, linearity is required for modern, wide band communication systems that must process signals with a wide dynamic range, but transistors and diodes are nonlinear devices.

RF/microwave MicroElectroMechanical Systems (MEMS) based devices were first demonstrated by Larson in 1991 [1] to be an alternative to solid-state devices for switches and varactors. Since that first paper, several variations of RF MEMS devices have been demonstrated including rotary switches [1], single supported cantilever metal-to-metal contact switches [2], double supported cantilever capacitive switches [3,4], and varactors [1]. Each of these devices shares common virtues [1-9]. They require high DC bias voltages ($10<V_{bias}<100$ V), but they draw nearly zero current and therefore consume negligible DC power. They have high linearity because they rely on simple metal-to-metal contacts or metal-insulator-metal (MIM) capacitors. These junctions also have very low loss to RF power; MEMS switches with 0.1 dB of insertion loss have been demonstrated at 30 GHz [3]. Lastly, and more importantly, MEMS devices may enable novel circuit and system designs and concepts that have not been possible before. For example, microfabrication processes developed for MEMS fabrication may be used to fabricate intricate metal shapes that cannot be fabricated using standard machining, such as novel RF high power amplifier circuit designs promising superior performance, but prohibited by conventional fabrication techniques.

NASA Glenn Research Center (GRC) has been actively fabricating, designing, and characterizing RF MEMS devices since 1997 for the advancement of space communication systems such as phased array antennas and receiver front ends. In this paper, we will present an overview of the development of RF MEMS switches, actuators, and varactors for frequency and phase reconfigurable components in NASA missions, their expected impact on communication systems, and issues that must be solved before MEMS devices may be fully utilized. In addition, a description of the use of microfabrication techniques to build a novel "finned-ladder Traveling Wave Tube (TWT) slow-wave structure" for more efficient, smaller size, lower cost power amplifiers at Ka-Band is presented.

II. RF MEMS SWITCHES FOR PHASE SHIFTERS

Figure 1 shows a schematic of a RF MEMS switch. The switch is implemented in Finite Ground Coplanar (FGC) waveguide with center strip conductor width (S), slot width (W), and ground plane width (G) of 50, 35, and 150 μm respectively, which yields a characteristic impedance of 50 Ω. A metal cantilever is built over this microwave transmission line using standard integrated circuit fabrication processes [5], and it is this cantilever that is the actuator. When no bias is applied to the structure, the cantilever remains a few microns above the FGC line, but when a potential difference is created between the transmission line and the cantilever, electrostatic forces of attraction cause the cantilever to be pulled down. A dielectric (Si_3N_4) covers the center strip conductor and ground planes of the FGC waveguide to prevent static friction or “stiction” between the bottom electrodes and the cantilever when they come into contact. Thus, these switches do not make a metal-to-metal contact as standard actuators do. The doubly supported cantilever spans the entire width of the transmission line, and the two supporting pads are separated from the ground plane by a 10 μm gap. Thus, the bias voltage applied to the cantilever is isolated from the transmission line, which permits a separate voltage to be applied to the center conductor of the FGC line for biasing diodes and transistors.

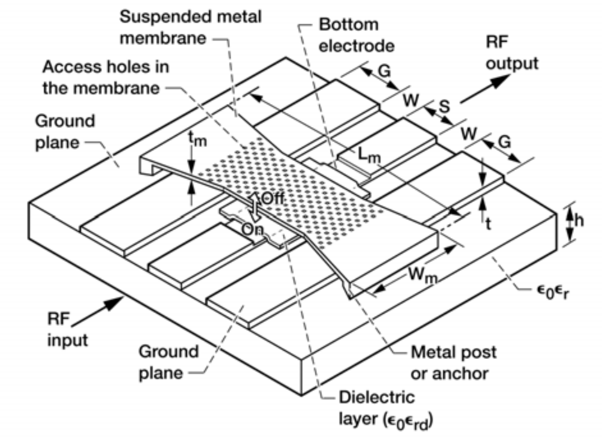

Figure 1: Schematic of the Finite Ground Coplanar Waveguide capacitive shunt MEMS

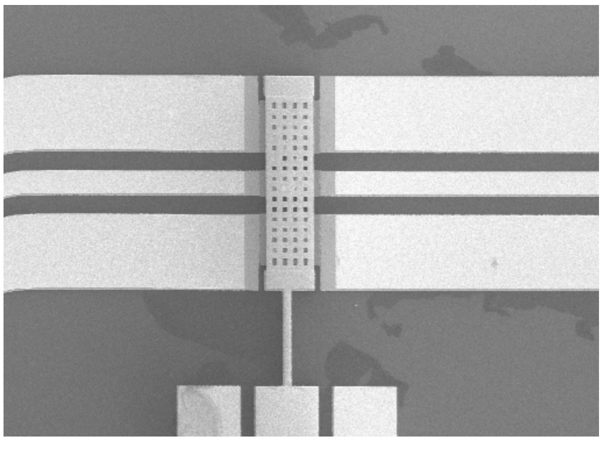

Figure 2: SEM image of FGC waveguide capacitive shunt MEMS switch.

When the cantilever is in the UP position, the parallel plate capacitance between the metal membrane and the bottom electrode, C_{OFF}, is small (approximately 0.05 pF) and the switch behaves as an open circuit. Hence, the signal transmission through the switch takes place with low insertion loss. In this state, the switch is said to be OFF. Conversely, when the cantilever is in the DOWN position, a metal-insulator-metal (MIM) capacitor is formed between the metal membrane and the bottom electrode. This on state capacitance, C_{ON}, is large (approximately 3 pF) and the switch creates an RF short circuit between the signal line and the ground planes. Hence, the signal is reflected back and the insertion loss is very high. A SEM picture of a typical MEMS switch fabricated on High Resistivity Silicon (HRS) at NASA GRC is shown in Figure 2.

The measured RF characteristics of the switch are shown in Figure 3. The isolation is 13 dB, the UP state return loss is better than 15 dB, and the UP state insertion loss is less than 0.15 dB at 26.5 GHz [5]. The design of the switch is being refined to increase the isolation to 30 dB at 26.5 GHz, which will enable these switches to be integrated into a 26.5 GHz, 5-bit phase shifter as shown in Figure 4 for use in a NASA phased array antenna demonstration. Note that RF MEMS switches do not decrease the phase shifter size, which is determined primarily by the delay lines, but they lower its insertion loss by 3.5 dB and consume negligible DC power.

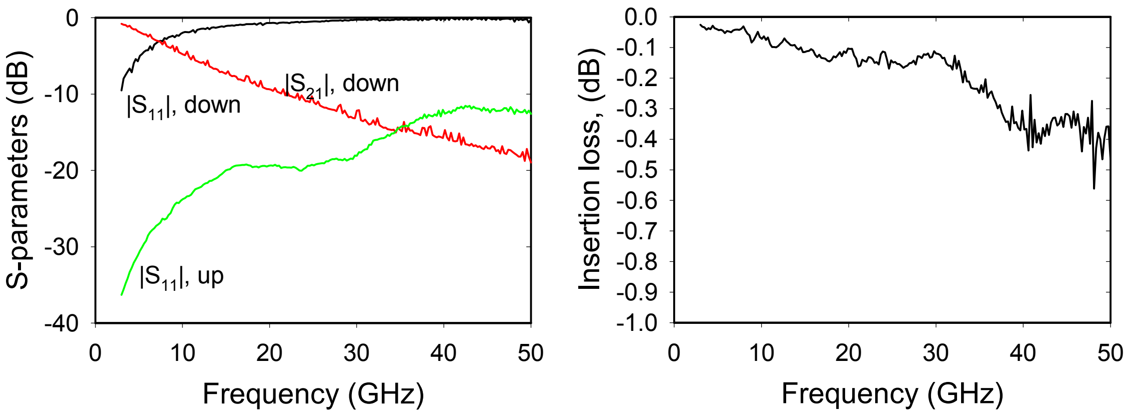

Figure 3: Measured RF characteristics of the FGC waveguide capacitive shunt MEMS switch.

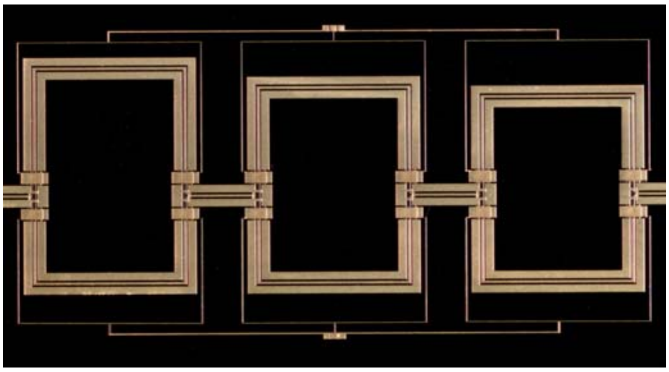

Figure 4: 26.5 GHz 3-bit phase shifter employing RF MEMS switches (6X16 mm).

III. MEMS ACTUATOR BASED SCANNING ANTENNAS

Besides RF MEMS switches for switched line phase shifters as described in the prior section, low loss, RF MEMS actuators may be used in novel ways to generate multiple beams or to move a single beam. Two types of beam shifting techniques are being developing by NASA GRC and the

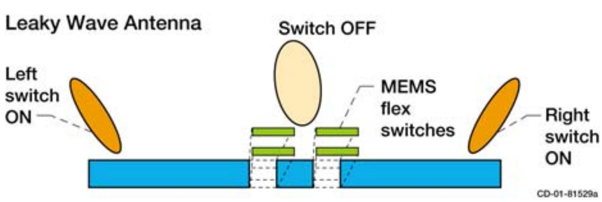

Figure 5: MEMS switched beam antenna.

University of Colorado. The first is a switched beam antenna that uses polymer-based MEMS flex actuators to switch between a probe fed patch antenna and two leaky wave structures placed symmetrically on both sides of the patch antenna as shown in Figure 5. The patch antenna has a broadside radiation pattern, while the leaky wave antennas have a radiation pattern that is tilted towards endfire with the amount of tilt dependent on the frequency. Thus, a broadside radiation pattern is obtained when the two MEMS switches are open and a left or right tilted radiation pattern is obtained when the left or right switch is closed respectively. In this configuration, three fixed beams can be generated from a single aperture. NASA GRC will build multi-element switched beam antennas at 26.5 GHz.

The second beam scanning technique that NASA GRC is developing is the use of MEMS actuators as variable capacitors, or varactors. By periodically loading a section of transmission line with variable capacitors, an artificial transmission line can be created with a variable propagation constant, or phase shift. Two types of variable capacitors are being developed. The first has a configuration similar to Figure 1, but instead of fully pulling the cantilever down and creating an RF short, the bias voltage is controlled so that the separation between the bottom electrode and the cantilever is controlled. This thermal actuated capacitor is shown in Figure 6. The second approach is shown in Figure 7, and it uses 20 cantilevers with different stiffness so that an applied voltage pulls down the cantilevers sequentially to create a variable capacitance with 20 capacitance states. These capacitors are fabricated using Cronos' MUMPS foundry processes with gold-on-polyisilicon structures and are integrated with coplanar waveguide (CPW) transmission lines using a flip chip die attach process.

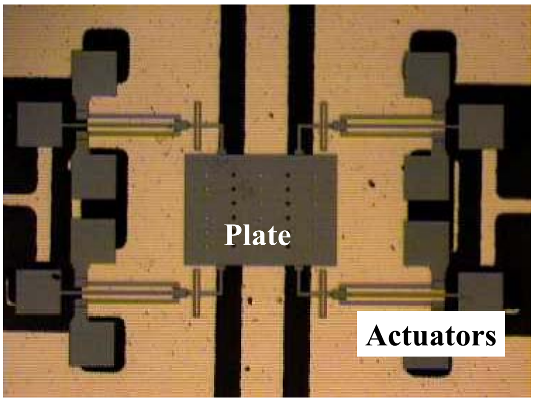

Figure 6: MEMS thermal actuated variable capacitor.

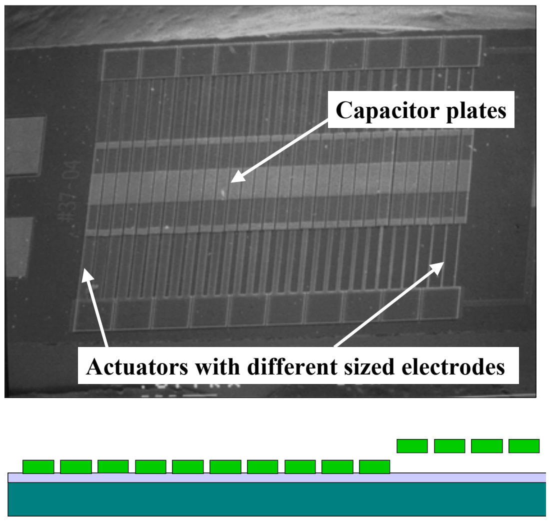

Figure 7: Cascaded variable capacitor

IV. RF MEMS ACTUATORS FOR FREQUENCY RECONFIGURABLE ANTENNAS

RF MEMS actuators may also be used for frequency agile antennas. NASA GRC has developed novel, frequency reconfigurable antennas by incorporating RF MEMS actuators with a microstrip patch antenna. Figure 8 shows the schematic of the reconfigurable antenna that uses two independent MEMS actuators. Each actuator is similar to the schematic shown in Figure 1, except instead of creating an RF short between the signal line and the ground lines of a RF transmission line, the actuator creates an RF short between the microstrip patch antenna and a small section of metal that increase the patch size. Since the patch dimensions determine the operation frequency of a microstrip patch antenna, the frequency of optimum radiation can be shifted to lower frequencies by activating the actuators and increasing the patch dimensions. Figure 9 shows an SEM photograph of the actuator.

The measured return loss for the reconfigurable antenna with independent actuators is shown in Figure 10 when both actuators are OFF. It is seen that the patch resonates at 25.0 GHz and has a 10 dB return loss bandwidth of 3.3 percent. When both actuators are ON, the resonant frequency shifts to 24.6 GHz as shown in Figure 10. However, either actuator may be actuated independently, and when this is done, the resonant frequency shifts to 24.8 GHz. This step change in resonant frequency by actuating one or both actuators is 200 and 400 MHz or 0.8 and 1.6 percent respectively. Lastly, note that the MEMS circuit does not affect the quality factor, or loss, of the antenna. By changing the length and width of the line added to the patch, the percentage change in resonant frequency can be varied over a wider range. For example, a reconfigurable patch has been demonstrated with a 15 percent dynamic change in frequency. These results, as well as the radiation patterns, are presented in [10-11].

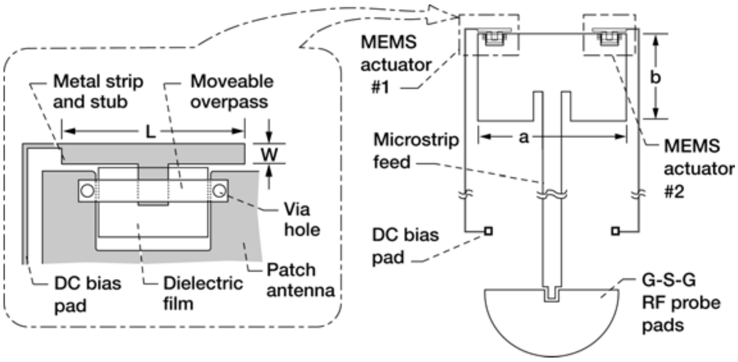

Figure 8: Schematic of frequency reconfigurable patch antenna with two independent MEMS actuators.

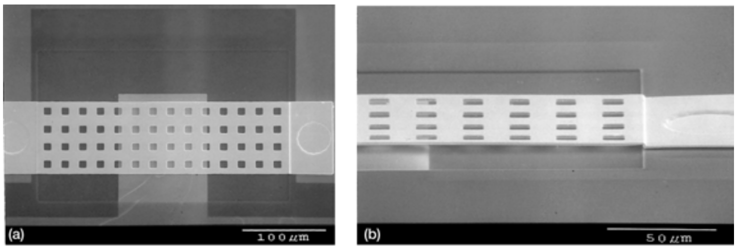

Figure 9: Photomicrograph of a MEMS actuator for reconfigurable antennas.

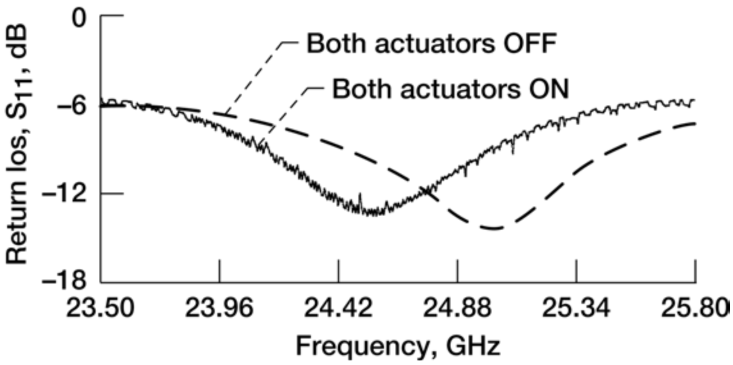

Figure 10: Measured return loss demonstrating frequency reconfigurability.

V. MICROMACHINED TRAVELING-WAVE TUBE AMPLIFIER

Transmission and retrieval of very large volumes of data from remote sensors for NASA missions requires high efficiency, high power amplification that can only be supplied by a traveling-wave tube (TWT) amplifier. A novel TWT interaction circuit, termed the "finned-ladder slow-wave structure", was designed using the unique computational capabilities at GRC. Compared to the state of the art, simulation results at Ka-band indicate major improvements in RF efficiency (1.5 times greater) and significantly reduced size and weight (up to a factor of 4 less). The small size of the circuit has prohibited its fabrication in the past using conventional machining approaches. However, an innovative fabrication process using micro-fabrication techniques is now being applied to build a finned-ladder TWT slow-wave structure.

The micro-fabrication method involves constructing two-dimensional (2D) pieces formed from a patterned structure like that shown in Figure 11 using batch chemical milling and/or micro-ElectroDischarge Machining (EDM) techniques. Each piece contains multiple circuit and/or spacer disks. These circuit and spacer disks are alternately stacked and diffusion bonded to form an all-metal periodic circuit structure as shown in Figure 12.

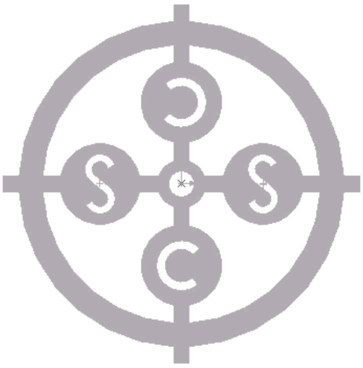

Figure 11: Conceptual view of patterned piece formed by chemical milling containing two circuit (C) and two spacer (S) disks (actual circuit not shown)

Critical fabrication requirements include straight sidewalls to avoid bridging in the small feature size gaps, extremely flat pieces for accurate periodicity, feature size accuracy (+/- 2.5 μm), and extremely smooth surfaces to minimize RF power losses. It is desired to have surface smoothness less than the skin depth at the operating frequency, which is typically less than one μm at Ka-band. Thus, special care must be taken to polish the disks before and after bonding.

Preliminary results indicate that this novel method provides an inexpensive and accurate fabrication process.

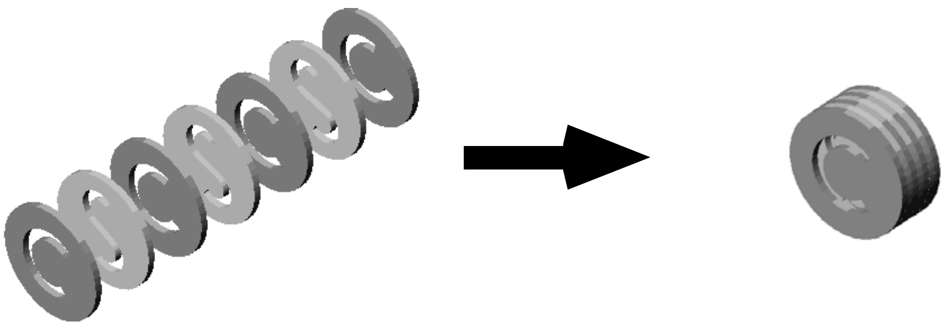

Figure 12: Circuit and spacer disks are alternately stacked and bonded to form 3D structure.

VI. DISCUSSIONS AND CONCLUSIONS

Several novel uses of RF MEMS actuators and the fabrication processes used to fabricate them have been presented. In this brief paper, we have shown that RF MEMS switches may be built using standard electronic fabrication processes with low insertion loss. Furthermore, these actuators may be used to build variable capacitors, or varactors, with low loss. Thus, RF MEMS actuators may replace GaAs MESFET transistor switches and diodes in standard phase shifters with a savings of 3.5 dB in insertion loss. Moreover, the flexibility to alter the size and shape of metal structures leads to even more exciting possibilities such as the reconfigurable antennas that we presented, and the precise fabrication of micron sized components enables the fabrication of new components that until now remained in designer's computers.

It is clear that MEMS offers some exciting possibilities to build better communication systems, especially at higher frequencies such as Ka-Band where electronic devices add considerable loss. However, the introduction of MEMS and MEMS fabrication processes into RF circuit design is relatively recent, and with time and experience, this technology will revolutionize microwave systems. The full impact of being able to change metal patterns on a circuit has not even been explored yet for tuning circuits, building filters, and creating integrated packages.

With the excitement of MEMS come some hard realities that must be addressed before their potential can be realized. Fabricating MEMS components relies on the removal of sacrificial layers to free the moving parts, and this step still affects yield in many processes. Also, the reliability and lifetime of mechanical moving parts and the wear of contacts that must be made and broken thousands of times a second are not fully understood. Thus, while the potential is great, research and development must still occur before MEMS components are available in the commercial market and integrated into space systems.

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